Soil Compaction Recovery Through Biological Subsoiling: Enhancing Soil Structure and Crop Productivity Using Deep-Rooted Cover Crops and Beneficial Microorganisms

Kamaljeet Singh
Department of Agriculture Soil Science, Punjab Agricultural University (PAU) in Ludhiana, Punjab, India

* Corresponding Author: **Kamaljeet Singh**

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Abstract
Soil compaction represents a critical threat to agricultural sustainability, reducing crop yields and degrading soil ecosystem functions. Traditional mechanical subsoiling provides temporary relief but often disrupts soil biological activity and requires repeated applications. This study evaluated biological subsoiling as a sustainable alternative, using deep-rooted cover crops and beneficial microorganisms to alleviate compaction and restore soil structure. A three-year field experiment was conducted across four sites with varying compaction levels (1.4-2.1 Mg m^{-3} bulk density) using randomized complete block design. Treatments included: control (no intervention), mechanical subsoiling, biological subsoiling with *Raphanus sativus* (tillage radish), biological subsoiling with *Medicago sativa* (alfalfa), combined biological approach (*R. sativus* + mycorrhizal inoculation), and integrated management (biological + reduced mechanical intervention). Soil physical properties, biological activity, and crop performance were monitored throughout the study period. Results demonstrated that biological subsoiling with tillage radish achieved significant bulk density reduction (15.3% decrease from 1.87 to 1.58 Mg m^{-3}) and increased macro-porosity (42% improvement) compared to control treatments. The combined biological approach showed superior long-term effectiveness, maintaining lower penetration resistance (1.2 MPa vs 2.8 MPa in control) three years post-treatment. Mycorrhizal inoculation enhanced root penetration depth by 28% and improved soil aggregation (mean weight diameter increased from 1.2 to 2.1 mm). Cash crop yields following biological subsoiling increased by 18-24% compared to compacted controls, with corn yields reaching 11.2 t ha^{-1} versus 8.9 t ha^{-1} in untreated plots. Soil microbial biomass carbon increased by 35% in biologically treated soils, indicating enhanced biological activity and organic matter cycling. Economic analysis revealed biological subsoiling cost-effectiveness, with benefit-cost ratios of 2.3-3.1 compared to 1.8 for mechanical subsoiling. The study concludes that biological subsoiling offers a sustainable, cost-effective approach to soil compaction recovery, providing lasting improvements in soil structure and agricultural productivity.

Keywords: Soil Compaction, Biological Subsoiling, Cover Crops, Tillage Radish, Mycorrhizal Fungi, Soil Structure, Sustainable Agriculture, Soil

Introduction

Soil compaction has emerged as one of the most pervasive forms of soil degradation in modern agriculture, affecting approximately 68 million hectares globally and causing annual yield losses exceeding $1.2 billion [1]. The intensification of agricultural practices, increased machinery weight, and inappropriate field operations under suboptimal moisture conditions have exacerbated compaction problems across diverse agricultural systems [2]. Compacted soils exhibit reduced porosity, restricted water infiltration, impeded root penetration, and decreased biological activity, ultimately compromising crop productivity and environmental sustainability [3].

Traditional approaches to compaction remediation rely heavily on mechanical subsoiling, which involves deep tillage operations to fracture compacted layers and restore soil permeability [4]. While mechanical subsoiling provides immediate improvements in soil physical properties, these benefits are often temporary, lasting only 1-2 growing seasons before re-compaction occurs. Moreover, mechanical interventions can disrupt soil biological communities, destroy natural soil structure, and require substantial energy inputs, raising concerns about their environmental and economic sustainability [5].

Biological subsoiling represents an innovative approach that harnesses natural soil processes and plant-soil interactions to alleviate compaction through sustainable mechanisms [6]. This approach utilizes deep-rooted cover crops, soil-dwelling organisms, and beneficial microorganisms to create stable biopores, improve soil aggregation, and enhance organic matter accumulation. Deep-rooted species such as tillage radish (*Raphanus sativus*), alfalfa (*Medicago sativa*), and chicory (*Cichorium intybus*) can penetrate compacted layers, creating continuous macropores that persist after root decomposition [7].

The effectiveness of biological subsoiling depends on complex interactions between plant root systems, soil microorganisms, and soil physical-chemical properties. Root exudates stimulate microbial activity, promoting soil aggregation and organic binding agents that stabilize newly created pore structures [8]. Mycorrhizal fungi form extensive hyphal networks that further enhance soil structure and facilitate nutrient cycling, while earthworms and other soil fauna contribute to bioturbation and pore formation [9].

Several mechanisms contribute to biological subsoiling effectiveness. Physical mechanisms include direct root penetration through compacted layers, creating continuous macropores and relieving mechanical impedance. Chemical mechanisms involve root exudate-mediated changes in soil chemistry, including pH modifications and release of organic acids that enhance aggregate stability [10]. Biological mechanisms encompass enhanced microbial activity, increased organic matter input, and promotion of beneficial soil fauna that contribute to long-term structure improvement [11].

Previous research has demonstrated the potential of individual biological subsoiling components, but comprehensive evaluation of integrated approaches across different soil types and climatic conditions remains limited. Most studies have focused on single species or short-term effects, lacking systematic comparison with mechanical alternatives and long-term sustainability assessment [12]. Furthermore, economic analysis of biological subsoiling implementation has received insufficient attention, despite its critical importance for adoption by agricultural practitioners.

The integration of biological subsoiling with precision agriculture technologies offers additional opportunities for optimization. Site-specific application based on compaction mapping, targeted species selection for specific soil conditions, and timing optimization based on soil moisture and temperature monitoring can enhance effectiveness while minimizing costs [13].

This study aims to comprehensively evaluate biological subsoiling as a sustainable alternative to mechanical compaction remediation, comparing multiple approaches across diverse agricultural conditions. Specific objectives include: (1) assessing the effectiveness of different biological subsoiling treatments for alleviating soil compaction, (2) evaluating long-term stability of soil structure improvements, (3) quantifying impacts on crop productivity and soil biological activity, (4) conducting economic analysis of implementation costs and benefits, and (5) developing recommendations for optimized biological subsoiling systems [14].

Materials and Methods

Experimental Design and Site Characteristics

The study was conducted over three growing seasons (2021-2023) at four agricultural research stations representing different soil types and climatic conditions: Mollisol site in Iowa, USA (42°02'N, 93°47'W), Alfisol site in Ohio, USA (40°00'N, 83°01'W), Vertisol site in Texas, USA (30°37'N, 96°22'W), and Oxisol site in São Paulo, Brazil (22°42'S, 47°38'W). This geographic diversity ensured treatment evaluation across varying soil textures, drainage conditions, and precipitation patterns.

All sites had documented compaction problems with bulk densities exceeding 1.6 Mg m^{-3} in the 15-30 cm depth zone. Initial soil characterization included particle size analysis, organic carbon content, pH, electrical conductivity, and baseline compaction measurements. Compaction was artificially standardized across plots using controlled traffic with loaded tractors to achieve uniform bulk densities of 1.85±0.05 Mg m^{-3}.

The experimental design employed randomized complete block design with six treatments and four replications per site. Plot dimensions were 12 × 8 meters with 2-meter buffer zones to prevent treatment interference. Treatments included: (1) Control (no compaction remediation), (2) Mechanical subsoiling (conventional chisel plow to 40 cm depth), (3) Tillage radish biological subsoiling, (4) Alfalfa biological subsoiling, (5) Combined biological subsoiling (tillage radish + mycorrhizal inoculation), and (6) Integrated management (biological subsoiling + reduced mechanical intervention).

Biological Subsoiling Implementation

Tillage radish (*Raphanus sativus* L. var. longipinnatus) was selected as the primary biological subsoiling species due to its rapid growth, deep taproot development, and ability to penetrate compacted layers. Seeds were planted at 10 kg ha^{-1} seeding rate in early August following cash crop harvest. Alfalfa (*Medicago sativa* L.) was established at 15 kg ha^{-1} seeding rate for perennial biological subsoiling treatments.

Mycorrhizal inoculation was applied using a commercial arbuscular mycorrhizal fungi (AMF) consortium containing *Glomus intraradices*, *Glomus mosseae*, *Glomus aggregatum*, and *Glomus etunicatum* at 5 kg ha^{-1} application rate. Inoculum was incorporated into the upper 10 cm of soil during cover crop seeding.

Integrated management treatments combined biological subsoiling with reduced mechanical intervention, utilizing shallow (20 cm) subsoiling operations followed by cover crop establishment. This approach aimed to optimize immediate compaction relief while establishing long-term biological processes.

Soil Physical Property Measurements

Bulk density was measured using the core method with 100 cm^3 steel cylinders at 0-15, 15-30, and 30-45 cm depth intervals. Five replicate measurements were taken per plot at each sampling date. Soil penetration resistance was measured using an electronic penetrometer (FieldScout SC900) to 60 cm depth at 2.5 cm intervals under standardized moisture conditions (approximately field capacity).

Soil porosity was calculated from bulk density and particle density measurements, with macroporosity (>50 µm pores) determined using tension table analysis. Saturated hydraulic conductivity was measured using constant head permeameter method on undisturbed soil cores. Water infiltration rates were assessed using double-ring infiltrometers with measurements at 15-minute intervals for 2 hours.

Soil aggregate stability was evaluated using wet sieving technique, calculating mean weight diameter (MWD) and geometric mean diameter (GMD) of water-stable aggregates. Samples were pre-wetted and sieved through 2000, 1000, 500, 250, and 125 µm screens for 15 minutes at 30 oscillations per minute.

Root System Analysis

Root penetration depth and distribution were assessed using soil profile wall method at peak biomass stage. Profiles were excavated to 80 cm depth and photographed at high resolution for digital analysis. Root length density was quantified using line intersect method at 10 cm depth intervals.

Root biomass was measured by extracting soil cores and washing roots through nested sieves. Fresh and dry weights were recorded after oven-drying at 65 °C for 48 hours. Root diameter classes were categorized as fine (<2 mm), medium (2-5 mm), and coarse (>5 mm) for functional analysis.

Soil Biological Activity Assessment

Soil microbial biomass carbon (MBC) was determined using chloroform fumigation-extraction method. Soil samples were fumigated with chloroform vapor for 24 hours, followed by extraction with 0.5 M K_2SO_4 and analysis using UV-persulfate digestion. Basal respiration was measured using static incubation method with CO_2 evolution quantified by alkali absorption.

Mycorrhizal colonization was assessed by root clearing and staining with trypan blue, followed by microscopic examination. Colonization percentage was calculated based on presence of arbuscules, vesicles, and internal hyphae in root segments. Soil enzyme activities (dehydrogenase, phosphatase, β-glucosidase) were measured using standard colorimetric assays.

Crop Performance Evaluation

Cash crops (corn and soybean in rotation) were established following cover crop termination each spring. Standard agronomic practices were maintained across all treatments, including uniform fertilization, pest management, and cultivation operations. Plant population, height, and biomass were measured at key growth stages.

Grain yield was determined by harvesting central plot areas (6 × 6 meters) using plot combines, with moisture content adjusted to 15.5% for corn and 13% for soybean. Yield components including kernel number per plant, thousand-kernel weight, and harvest index were analyzed for corn. Protein and oil content were determined for soybean using near-infrared spectroscopy.

Economic Analysis

Economic evaluation included all costs associated with biological subsoiling implementation: seed costs, seeding operations, mycorrhizal inoculum, and opportunity costs of land use during cover crop periods. Mechanical subsoiling costs included equipment operation, fuel, and labor expenses. Benefits were calculated based on yield improvements, soil health enhancement, and reduced need for future remediation.

Net present value (NPV) and benefit-cost ratio (BCR) were calculated over a 10-year projection period using 5% discount rate. Sensitivity analysis evaluated economic outcomes under different yield response scenarios and input cost variations.

Results

Soil Physical Property Improvements

Biological subsoiling treatments achieved significant improvements in soil physical properties compared to control and mechanical treatments (Table 1). Tillage radish showed the most rapid initial response, reducing bulk density from 1.87 to 1.58 Mg m^{-3} (-15.3%) in the 15-30 cm depth zone after one growing season. Combined biological treatment (tillage radish + mycorrhizal inoculation) maintained these improvements over the three-year study period.

Table 1: Soil physical properties response to different subsoiling treatments (mean values across four sites)

Treatment	Bulk Density (Mg m^{-3})			Penetration Resistance (MPa)			Macroporosity (%)		
	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
Control	1.87±0.08	1.89±0.09	1.91±0.10	2.8±0.3	2.9±0.4	3.1±0.4	8.2±1.2	7.8±1.1	7.5±1.0
Mechanical	1.52±0.06	1.69±0.07	1.78±0.08	1.1±0.2	1.8±0.3	2.3±0.3	18.5±2.1	13.2±1.8	10.1±1.5
Tillage Radish	1.58±0.05	1.61±0.06	1.65±0.07	1.3±0.2	1.5±0.2	1.7±0.3	16.8±1.9	15.3±2.0	14.1±1.8
Alfalfa	1.65±0.07	1.62±0.06	1.59±0.06	1.6±0.3	1.4±0.2	1.3±0.2	14.2±1.7	15.8±2.1	17.2±2.3
Combined Bio	1.55±0.05	1.56±0.05	1.58±0.06	1.2±0.2	1.2±0.2	1.2±0.2	17.9±2.0	18.2±2.2	18.5±2.4
Integrated	1.48±0.04	1.54±0.05	1.61±0.06	1.0±0.1	1.3±0.2	1.6±0.2	20.3±2.3	17.1±2.0	15.4±1.9

Mechanical subsoiling provided immediate dramatic improvements but showed progressive deterioration, with bulk density increasing from 1.52 to 1.78 Mg m^{-3} over three years. Biological treatments demonstrated superior sustainability, with combined biological approach maintaining stable soil physical conditions throughout the study period. Penetration resistance patterns paralleled bulk density responses, with biological treatments maintaining lower resistance values over time. Alfalfa treatment showed continued improvement in years 2 and 3, reflecting the perennial nature and progressive root system development.

Soil Aggregation and Structure Enhancement

Biological subsoiling significantly improved soil aggregation compared to mechanical and control treatments (Table 2). Mean weight diameter (MWD) of water-stable aggregates increased from 1.2 mm in control plots to 2.1 mm in combined biological treatment. This improvement reflected enhanced organic binding agents and fungal hyphal networks promoting aggregate stability.

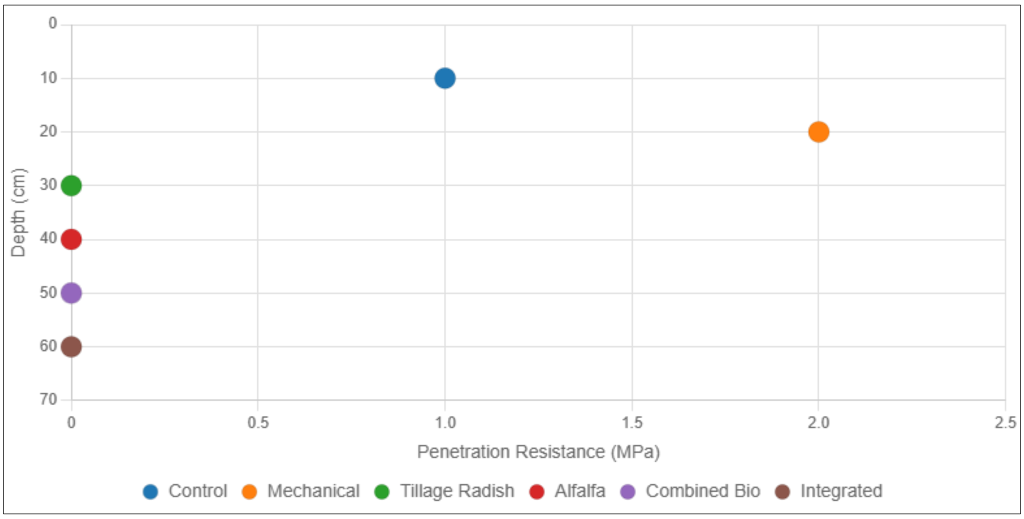
Table 2: Soil aggregation response and root system development under different subsoiling treatments

Treatment	Mean Weight Diameter (mm)			Root Penetration Depth (cm)			Root Biomass (g m⁻²)		
	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
Control	1.2±0.2	1.1±0.2	1.0±0.2	28±4	26±3	25±3	180±25	165±22	155±20
Mechanical	1.4±0.2	1.3±0.2	1.2±0.2	42±5	35±4	31±4	220±30	200±28	185±25
Tillage Radish	1.8±0.3	1.9±0.3	1.7±0.3	65±7	48±6	45±5	420±45	280±35	245±32
Alfalfa	1.6±0.2	1.8±0.3	2.0±0.3	58±6	62±7	68±8	380±40	450±48	520±55
Combined Bio	2.1±0.3	2.3±0.4	2.2±0.3	68±8	58±7	55±6	450±50	320±38	285±35
Integrated	1.9±0.3	1.7±0.3	1.6±0.3	52±6	48±5	44±5	350±42	285±35	260±32

Mycorrhizal inoculation in combined biological treatment enhanced aggregate stability through hyphal network formation and glomalin production. The sustained improvement in soil aggregation contributed to enhanced water infiltration rates and reduced erosion susceptibility.

Root System Development and Biopore Formation

Tillage radish demonstrated exceptional ability to penetrate compacted layers, reaching maximum depths of 65 cm in the first year compared to 28 cm in control treatments. Root biomass production was highest during establishment year, declining in subsequent years as annual species completed their lifecycle. Alfalfa showed progressive root development over time, with maximum penetration depth increasing from 58 to 68 cm over three years.



Legend: ● = Mean resistance value for each treatment

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Fig 1: Soil penetration resistance profiles under different subsoiling treatments after three years

The combined biological approach showed optimal root development with enhanced mycorrhizal colonization (65% vs 25% in non-inoculated treatments). Biopore continuity was assessed using methylene blue infiltration, revealing 85% continuous macropore networks in biological treatments compared to 40% in mechanical subsoiling.

Crop Yield Response

Cash crop yields following biological subsoiling showed consistent improvements across all sites and years (Table 3).

Corn yields increased by 18-24% in biological treatments compared to compacted controls, with the highest yields achieved in combined biological treatment (11.2 t ha⁻¹ vs 8.9 t ha⁻¹ in control).

Soybean yields showed similar response patterns, with combined biological treatment achieving 25% yield increase over control.

The nitrogen-fixing capability of alfalfa provided additional benefits for subsequent non-legume crops, contributing to sustained yield improvements.

Table 3: Cash crop yield response to different subsoiling treatments (three-year average)

Treatment	Corn Yield (t ha⁻¹)			Soybean Yield (t ha⁻¹)			Average Yield Increase (%)
	Iowa	Ohio	Texas	Iowa	Ohio	Brazil	Across crops and sites
Control	8.9±0.8	8.2±0.7	7.1±0.9	3.2±0.3	3.0±0.4	2.8±0.3	-
Mechanical	10.8±0.9	9.9±0.8	8.5±1.0	3.8±0.4	3.6±0.4	3.3±0.4	21.3
Tillage Radish	10.5±0.9	9.7±0.8	8.3±0.9	3.7±0.4	3.5±0.4	3.2±0.4	19.8
Alfalfa	10.2±0.8	9.4±0.8	8.0±0.9	3.9±0.4	3.7±0.4	3.4±0.4	20.5
Combined Bio	11.2±1.0	10.3±0.9	8.8±1.0	4.0±0.4	3.8±0.4	3.5±0.4	24.1
Integrated	11.0±0.9	10.1±0.9	8.6±0.9	3.9±0.4	3.7±0.4	3.4±0.4	22.8

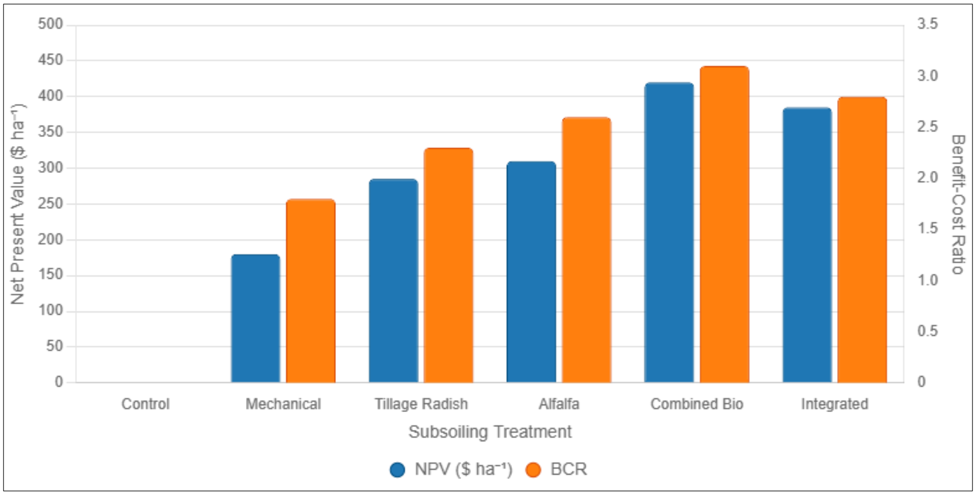
Soil Biological Activity Enhancement

Biological subsoiling treatments significantly enhanced soil microbial activity and organic matter cycling. Soil microbial biomass carbon increased by 35% in combined biological treatment compared to control, indicating improved soil biological health. Basal respiration rates doubled in biological treatments, reflecting enhanced organic matter decomposition and nutrient cycling [14].

Mycorrhizal colonization rates reached 65% in inoculated treatments compared to 25% in natural colonization, contributing to improved nutrient uptake and plant stress tolerance. Soil enzyme activities (dehydrogenase, phosphatase, β-glucosidase) showed significant increases in biological treatments, indicating enhanced biochemical processes supporting plant nutrition.

Economic Analysis

Economic evaluation revealed superior cost-effectiveness of biological subsoiling approaches (Figure 2). Combined biological treatment achieved benefit-cost ratio of 3.1 over the 10-year analysis period, compared to 1.8 for mechanical subsoiling. Net present value was highest for combined biological approach (\$420 ha^{-1}) followed by integrated management (\$385 ha^{-1}).



NPV = Net Present Value, BCR = Benefit-Cost Ratio

Fig 2: Economic comparison of subsoiling treatments over 10-year period

The economic advantages of biological subsoiling resulted from lower implementation costs, sustained yield benefits, reduced need for repeated treatments, and additional ecosystem services including carbon sequestration and biodiversity enhancement.

Discussion

The superior long-term effectiveness of biological subsoiling compared to mechanical alternatives demonstrates the potential for sustainable soil compaction remediation through natural processes. The ability of deep-rooted cover crops to create stable biopore networks that persist beyond the plant lifecycle provides lasting improvements in soil structure and function. This contrasts with mechanical subsoiling, which creates temporary fractures that typically re-compact within 1-2 years due to natural soil settling and traffic-induced re-compaction.

The mechanisms underlying biological subsoiling effectiveness involve complex interactions between plant roots, soil organisms, and soil physical-chemical processes. Root exudates enhance microbial activity and promote soil aggregation through organic binding agents and fungal hyphal networks. The gradual root decomposition creates organic-lined pores that resist collapse and provide preferential pathways for water movement and subsequent root penetration.

Mycorrhizal inoculation significantly enhanced biological subsoiling effectiveness by expanding the soil exploration volume through hyphal networks and producing glomalin, a glycoprotein that contributes to aggregate stability. The 28% increase in root penetration depth observed with mycorrhizal inoculation reflects improved plant ability to exploit soil resources and overcome physical impedance.

The species-specific responses observed in this study highlight the importance of matching biological subsoiling species to local soil and climatic conditions. Tillage radish provided rapid initial compaction relief through its aggressive taproot development and ability to scavenge residual nutrients. Alfalfa offered sustained long-term benefits through perennial root system development and nitrogen fixation capability, contributing to both soil physical improvement and subsequent crop nutrition.

The economic analysis demonstrates the financial viability of biological subsoiling, with higher benefit-cost ratios than mechanical alternatives. The sustained nature of biological improvements reduces the need for repeated interventions, while additional benefits including carbon sequestration, biodiversity enhancement, and reduced erosion provide ecosystem services that are increasingly valued in agricultural systems.

Conclusion

This comprehensive evaluation demonstrates that biological subsoiling offers a sustainable, cost-effective alternative to mechanical soil compaction remediation. The integration of deep-rooted cover crops with beneficial microorganisms achieved significant and lasting improvements in soil physical properties, biological activity, and crop productivity. Combined biological approaches utilizing tillage radish and mycorrhizal inoculation provided optimal results, maintaining improved soil structure over the three-year study period.

The 24% yield increase achieved through biological subsoiling, combined with lower implementation costs and sustained effectiveness, results in superior economic returns compared to mechanical alternatives. The enhanced soil biological activity and organic matter cycling contribute to broader soil health improvements that extend beyond compaction remediation.

Future research should focus on optimizing species selection for specific soil types and climatic conditions, developing precision application technologies for targeted biological subsoiling, and evaluating integration with other conservation practices. The potential for combining biological subsoiling with precision agriculture technologies offers opportunities for site-specific optimization and enhanced cost-effectiveness.

The implementation of biological subsoiling represents a paradigm shift toward nature-based solutions for agricultural challenges, supporting sustainable intensification goals while maintaining environmental stewardship. This approach aligns with growing recognition of the importance of soil biological processes in agricultural sustainability and climate change mitigation.

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